Parameters of walkability: A meta-analysis

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Author(s):
Urech, Samuel; Meeder, Mark

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Parameters of walkability: A meta-analysis

Identifying and defining objective walkability parameters.

Samuel Urech

Mark Meeder

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IVT Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Samuel Urech, Mark Meeder

Wesemlinstrasse 19
CH-6006 Luzern
phone: +41-79-851 50 43

samuel.urech@bluewin.ch

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Abstract

Walkability can be understood as the walk-friendliness of a built environment. A wide range of walkability attributes are reported and measured in existing literature. However, a consensus on the relative importance of each parameter does not exist. General models for the interactions between pedestrians and their environment have only been suggested in a rudimentary form. To address these issues, an in-depth research of the relevant literature is conducted. The relevant publications on the topic are collected and categorized in four major "schools" of walkability research. From these sources, all environmental attributes that affect walk-friendliness are collected in a spreadsheet and sorted into to a number of generalised parameters. This list represents the first result of the paper: A more objective overview of all known influencing parameters of walkability, each defined clearly and unambiguously. In a further step, a number of analyses are carried out in order to compare the reported coefficients of said parameters, with the goal of estimating their effect size on walking satisfaction and walking activity. The results enable a ranking of walkability parameters based on their relative importance. Besides walking distance, which leads all walking influences by a large margin, the presence of comfortable and uninterrupted walking infrastructure, the absence of cars and good street connectivity are found to be most important for pedestrians. This research thus provides a quantitative comparison of walkability influences that to this extent has been absent from the field. The structured presentation and subsequent discussion provide a basis for practical implementation as well as further research.

Keywords

Pedestrian transport, Walkability, Walkable neighborhoods, Meta-Analysis, Walkability parameters, Pedestrian properties, Pedestrian wayfinding, Streetscape design

Preferred citation style

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1 Aim of this research

Walking as transport mode and pedestrian-oriented city planning have increased in importance since the New Urbanism movement of the 1970s and 1980s (Congress for the New Urbanism, 2000). The concept of liveable streets for pedestrians was introduced by Appleyard (1980) as an alternative for car-centric design. Around that time, the term *walkability* starts appearing in the literature. It describes the suitability and quality of a built environment to walk and to linger as a pedestrian (Frank et al., 2010), and is roughly synonymous with walk-friendliness. A large field of research is dedicated to understanding the relationship between walkability and transport behaviour (Cervero and Kockelman, 1997), physical activity and health (Handy et al., 2002; Brownson et al., 2009; Van Dyck et al., 2011). Particularly in the late 1990s and early 2000s, a sizeable number of studies analyse which parameters of the built environment affect walkability and therefore pedestrians' behaviour. Some examine entire neighbourhoods (Leslie et al., 2005; Cerin et al., 2007) while others focus on individual street segments (Dixon, 1996; Landis et al., 2001).

Although various more or less established walkability indicators have been suggested, it is not readily understood which parameters of the built environment actually matter for pedestrians and how much each of them influences their behaviour and satisfaction. Moreover, definitions of individual parameters differ considerably, and in many cases no reasoning or source is given for their selection. This is surprising as the studies in question aim to measure walkability and determine and which parameters are relevant. Only a handful of meta-analyses of said studies exist, Saelens and Handy (2008) and Owen et al. (2004) being two of the most-cited. General models of the perceptions and needs of pedestrians are equally rare. A paper by Alfonzo (2005) offers a rudimentary framework, which appears to have not been verified or further pursued.

This study is aimed at providing two main results, based on a meta-analysis of quantitative walkability literature. First, a systematic overview of existing walkability parameters is established in order to identify which variables should be part of walkability models. The more often a parameter appears in the literature, the more likely its relevance for describing walkability. Such a compilation of parameters could facilitate the development of future models. In a second step, the relative importance of parameters featured in the literature was calculated. Knowledge of which walkability parameters are more important helps better understand the needs of pedestrians and could facilitate further research. These insights could also be of practical use in transport planning and urban design.

2 Research Method

2.1 Literature review

In a first step, an in-depth literature research is carried out to gather relevant sources from the different sub-fields of walkability research such as the influence of the built environment on pedestrians, their orientation and wayfinding processes and the perception of their environment. Studies examining one or more specific parameters of walkability are collected in a spreadsheet. In total, 202 relevant literature sources are identified and sorted into four distinct categories to give a thematic overview of the state of the literature:

- **A) Health, physical activity and the built environment**: Examination of the relationship between walking, health, transport modes and the built environment. Focus on so-called environmental correlates of walking, usually neighbourhood based. Research disciplines: Medicine, often in collaboration with geographers, spatial or transport planners.
- **B) Pedestrians: properties, preferences, perception and behaviour**: Research aimed at a better understanding of pedestrian transport through surveys or observation. Often focused on one aspect of walkability, like walking speed, trip length, or streetscape aesthetics. Research disciplines: Social sciences and transportation science.
- **C) Spatial cognition, orientation and choice modelling**: Similar to Category B) but more data-driven and with a more traditional scientific approach. Research disciplines: Sciences with a strong focus on modelling (like physics, mathematics, or economics).
- **D) Walkability in architecture, spatial and transport planning**: Applied research with a focus on spatial planning and transport engineering practice. This is the broadest category, ranging from architectural essays to mobility and zoning plans to traffic engineering experiments. It can involve idealistic aspects, arguing for or against public policies. Research disciplines: Urban planning, architecture, transportation and environmental engineering.

The allocation of publications to the four categories is based on the field of research of the authors as well as the publications' keywords and abstracts. The suggested categories are not carved in stone and some of the 202 sources cannot clearly be assigned to one. However, the authors believe that structuring the literature in this way makes the most sense and has some merit: The entire field can be better understood and the research results may be put into practice more efficiently. For every literature category, some prominent publications are discussed and the main results are summarized. The same categories were used to structure the meta-analysis in the latter part of this paper.

2.2 Definition of generalised walkability parameters

Based on the literature review, a meta-analysis was conducted to find objective parameters that describe the walkability of the built environment. In order to do so, the 202 literature sources were reduced to only those explicitly aimed at measuring environmental parameters that influence walkability, totalling 24, as displayed in Table 1. For each study, the measured parameters were recorded systematically in a spreadsheet, recording the original definition and unit of the parameter as well as its effect size with respect to perceived walkability (for example, the β coefficient if a regression model was fitted). In addition to the literature categories presented above, another systematic structure was established to account for spatial scale. The following three levels were defined and used to describe the spatial resolution of each parameter:

- **Microscopic**: Parameters describing the immediate vicinity of pedestrians, usually properties of individual street segments or cross-sections. These usually influence pedestrians directly and in the moment, e.g. walking surface, the presence of a sidewalk, or obstacles.
- **Mesoscopic**: Parameters measured or observed for several segments at once, usually individual streets extending in one direction or parts of neighbourhoods. This scale is associated most with streetscape design or placemaking. Examples are the aesthetics of a street or the arrangement of its buildings.
- **Macroscopic**: Entire areas, multiple places and streets connected and combined into a neighbourhood. Measured parameters are usually aspects of land-use, population or business densities. They are often not experienced directly by pedestrians.

As an intermediate result, the spreadsheet contains 215 parameters, many of which are identical, obtained from the 24 selected studies. By grouping all parameters describing the same quantity or phenomenon (for example all parameters describing the influence of sidewalk width on walkability), the collection was categorized in 35 "buckets". Based on the names and descriptions used in the original literature sources of the original parameters in each group, generalised walkability parameters were defined. For example, for the various studies that researched the effect of trees and green spaces on pedestrians, the generalised parameter was labelled "Trees/green". The corresponding pool of parameters contains values from the literature for the number of trees on a segment, the amount of m^2 of green space, etc. This systematic and generalised set of walkability parameters is presented in Table 2 as a first result of the meta-analysis. A more detailed description is found in the Results section.

Table 1: Overview of sources used for the meta-analysis of walkability literature. Sources marked with A and/or B are used for rating Methods A and B, respectively. The numbers in the column with generalised parameters correspond to those in Table 2.

Source	Literature category	Sample size	Scale	Generalised parameters
Barros et al. (2015)[B]	C	599	mesoscopic	3, 4, 6, 9, 10, 15, 18, 22, 23, 24, 31, 33
Bernhoft and Carstensen (2008)	B	1905	microscopic	1, 4, 6, 7, 22, 30, 35
Blecic et al. (2016)[AB]	D	408	mesoscopic	3, 5, 6, 11, 13, 14, 15, 18, 22, 23, 25, 28, 31, 33, 34
Broach and Dill (2015)[B]	C	1167	mesoscopic	1, 4, 6, 7, 10, 13, 15, 17, 30, 32, 35
Cervero and Duncan (2003)	D	7889	mesoscopic	10, 16, 19, 22, 28, 35
Christopoulou and Pitsiava (2012)	D	-	microscopic	2, 3, 4, 9, 11, 21, 24, 27, 29, 30, 31, 32
Craig et al. (2002)[B]	A	10983	macroscopic	1, 2, 12, 13, 14, 16, 19, 21, 22, 26, 27, 32
De Bourdeaudhuij et al. (2003)[A]	A	526	macroscopic	1, 16, 18
Dixon (1996)	D	-	mesoscopic	1, 2, 5, 6, 11, 15, 23, 24, 30, 31, 32
Ewing et al. (2006)[AB]	D	48	mesoscopic	5, 12, 13, 26
Ferrer et al. (2015)	D	23	microscopic	2, 3, 14, 21, 26, 27
Frank et al. (2005)[A]	A	357	macroscopic	16, 19, 20
Frank et al. (2010)	D	2400	macroscopic	16, 18, 19, 20
Guo and Loo (2013)	C	276	mesoscopic	3, 6, 13, 17, 27, 29, 30, 35
Kang and Fricker (2016)	B	114	mesoscopic	3, 11, 24, 28, 30, 34
Kim et al. (2014)[AB]	B	74644	macroscopic	3, 6, 7, 8, 9, 10, 16, 19, 20, 22, 23, 24, 32
Kim et al. (2016)[AB]	D	1407	macroscopic	1, 8, 10, 14, 16, 20, 21, 27, 33
Landis et al. (2001)	D	1250	microscopic	2, 11, 25, 30
Leslie et al. (2005)	D	87	mesoscopic	1, 14, 16, 19, 20, 21, 27, 35
Moura et al. (2017)	D	289	microscopic	4, 5, 10, 21, 27, 29
Oreskovic et al. (2014)[B]	D	45	mesoscopic	12, 13, 14, 26, 31
Rodríguez et al. (2009)	D	338	mesoscopic	2, 3, 6, 16, 19, 20, 23, 28
Shay et al. (2009)	D	251	microscopic	1, 2, 3, 4, 6, 7
Smith (2009)	B	282	mesoscopic	1, 5, 6, 7, 16, 19, 24

2.3 Parameter rating

Despite the efforts of many scholars to measure the influence of many environmental parameters on the walk-friendliness of a street or an area, a clear consensus on the relative importance of each parameter has not been reached. Therefore, a quantitative comparison of such studies may lead to valuable insights about which attributes to focus on or invest in. The parameter collection described above is used to achieve this. The analysed studies are only partly suited for a direct comparison of coefficient values as only a handful of sources report standardized effect sizes. In order to consider more literature than those few sources, an alternative method of meta-analysis is employed for rating each individual parameter. In this second method, the relative importance of each parameter within a certain study is evaluated. These values are subsequently averaged across all sources in which the parameter appears. Ten out of the 24 literature sources used for collecting walkability parameters are suited for a quantitative comparison of individual parameters. Six out of those ten can be used for averaging effect sizes, while eight are used for evaluating the relative importance of parameters.

Method A: Weighted average effect size

For the sources that report standardized effect sizes, the weighted average of all effect sizes of a specific generalised parameter β_{M} should give an accurate estimate for the true effect size of said parameter. This method of meta-analysis is well-established (Hunter and Schmidt, 2004). Since only a small number of studies report variances, the sample sizes are used for weighting. To avoid giving undue importance to a single study with a very large sample size, the effect sizes β_{i} from the N studies in which said generalised parameter occurs are weighed with the square roots of their sample sizes n_i:

$$\beta_M = \frac{\sum_{i=1}^{N} \sqrt{n_i}\beta_i}{\sum_{i=1}^{N} \sqrt{n_i}} \tag{1}$$

This method yields an estimate of the quantitative influences of environmental parameters on walkability. However, as mentioned above not many studies report standardized effect sizes, and there are several more reasons why comparing average effect sizes can be problematic in this field of research.

Method B: Relative importance

A known issue with meta-analyses is that differences between the models fitted in different studies can be very large. This particularly applies in this field of research where a variety of research methods are applied, ranging from pedestrian surveys or analysing census results to showing videos of street scenes to a panel of experts. Some studies feature a broad range of parameters from sidewalk measures to population statistics and building aesthetics while others focus on a much narrower research area. For these reasons, comparing average effect sizes can be problematic, even more so since some parameters are easier to measure quantitatively than others are. Furthermore, the explained variable, a measure for (perceived) walkability of a place or area, is not easily defined. This is exacerbated by the fact that people's preferences concerning walkability as well as the environmental and cultural influences vary across regions. Consequently, one should be careful with interpreting the *absolute* size of a parameter's effect on walkability.

In addition to these general issues, the reporting of effect sizes in walkability research vastly differs between studies. Some researchers report partial correlation coefficients, which enable a clean comparison of effect sizes. Unfortunately, these cases are rare: Only three studies in the selection of 24 report partial correlations between environmental parameters and (perceived) walkability. In other cases bivariate correlations are reported, which can only be compared between studies when cross-correlations are sufficiently small. Still more studies report raw model coefficients, which can often not be compared between studies because of differences in the models themselves or in the definitions of said parameters (including their measurement units). To be able to compare environmental influences on walkability quantitatively across as many studies as possible a simple measure for relative importance (Kruskal and Majors, 1989) was employed as a second rating method. For each of N eligible studies, the amount of variance explained by a specific parameter j in the model in question is divided by the total amount of variance explained by all P environmental parameters in the model:

$$RI_i = \frac{\mid \beta_i \mid}{\sum_{j=1}^{P} \mid \beta_j \mid} \tag{2}$$

This value RI_i thus lies between zero and one and is higher for parameters that explain more variance in (perceived) walkability. According to the generalised parameter collection presented above, the RI_i values were allocated to the appropriate parameter. For each generalised parameter, the weighted average relative importance RI_M across all N contributing studies was calculated using the same weights as in Method A:

$$RI_M = \frac{\sum_{i=1}^{N} \sqrt{n_i} RI_i}{\sum_{i=1}^{N} \sqrt{n_i}} \tag{3}$$

This way of determining the relative contribution of independent variables is a much more simplified version of relative importance analysis than is usually encountered in the literature. Tonidandel and LeBreton (2011) discuss two more commonly used techniques as well as their place alongside regression analysis. Contrary to those methods, the implementation of relative importance used here does not intend to eliminate correlations between independent variables. The goal is rather to increase the number of evaluated studies by enabling the quantitative comparison of studies that use different measures for the same parameter. As rating method B solely requires parameters to be comparable within a study, rather than between studies, contributions from more studies can be used to calculate the averages of all parameters, increasing the reliability of quantifying environmental influences on walkability. The exact criteria for whether a study was used in either of the rating methods A and B are listed in the results section below.

One obvious weakness of Method B in comparison with Method A is that is relies more on the correctness of models in the respective studies. Specifically, if a model features fewer parameters, the relative importance of each parameter increases inherently. This increase is only valid if the model explains roughly as much variance in walkability as models from other studies that feature more parameters. A second trade-off is made with regard to the signs of effect sizes of environmental parameters. Method B does not discriminate between negative or positive influences on walkability. Therefore, if different studies report opposite effects of the same parameter, this distinction is lost, potentially resulting in rating said parameter too highly. Whether these weaknesses are offset by the increased reliability of using data from a higher number of sources is discussed below.

3 Literature Review

3.1 Distinct categories of walkability literature

A) Health, physical activity and the built environment Many studies seek to link physical activity and other health-related data with urban design attributes. A pedestrian-friendly urban design is thought to induce more trips on foot and to therefore generally improve public health. Due to an increase in obesity and cardio-vascular diseases because of deficient physical activity (Brownson et al., 2009), this issue gained increased interest among researchers. Siegel et al. (1995) state the importance of walking as the most basic physical activity and review the influence of socio-economic attributes. Many studies have found significant associations between activity and built environment parameters (Handy et al., 2002; De Bourdeaudhuij et al., 2003; Frank et al., 2006; Badland and Schofield, 2005). Humpel et al. (2002) corroborate these results through a meta-analysis and find that the accessibility of facilities, opportunities for activity and aesthetics show significant correlation with physical activity. Some studies explore the influence of pollution caused by traffic (Killingsworth, 2003; Marshall et al., 2009) while others examine the possible self-selection of walking determinants (Van Dyck et al., 2011; Carnegie et al., 2002).

B) Pedestrians: properties, preferences, perception and behaviour Alfonzo (2005) suggested a pyramidal hierarchy of needs for pedestrians based on existing research. This pedestrian model is one of the few existing theoretical frameworks within the topic. Gehl et al. (2006) offer a detailed discussion of building façades and dimensions and their perception by pedestrians. Many others have researched the influence of aesthetics and streetscape design on pedestrians (e.g. Ulrich, 1986; Weber et al., 2008).

The ability to estimate distances affects perceived walkability. McCormack et al. (2008); Macintyre et al. (2008) show that pedestrians struggle to do this correctly, a result reproduced and expanded upon by others (Macintyre et al., 2008; Hess, 2012; Armeni and Chorianopoulos, 2013; Hernández and Witter, 2015).

A survey by Bernhoft and Carstensen (2008) tests route choice preferences of both older and younger pedestrians; the presence of a smooth sidewalk and walking distance are reported as significant. Ferrer et al. (2015) collects qualitative statements in pedestrian focus groups, adding value to the mostly statistical results of other researchers. Barros et al. (2015) add the influence of car availability to other typical walkability parameters in a discrete choice survey.

C) Spatial cognition, orientation and choice modelling Bovy and Stern (1990) and Golledge (2004) give overviews on the general process of wayfinding: Pedestrians access their spatial knowledge, consisting of known routes, route attributes and landmarks, and compare this with perceptions and observations of the built-environment in order to reach their destination. Meilinger et al. (2013) report on differences between wayfinding from experience and with maps. The role of landmarks is vital for pedestrians' orientation and is the topic of many studies (Raubal and Winter, 2002; Richter and Winter, 2014a; Meilinger et al., 2016; Nuhn and Timpf, 2017). Körner et al. (2012) research the details of visual perception, an area in which technical advances like eye-tracking and virtual reality have enabled new approaches (Simpson et al., 2018; Franke and Schweikart, 2017). Lastly, although route choice modelling has a long tradition in transportation science, specific models for pedestrians are a recent development (Davies and Pederson, 2001; Li, 2006; Giannopoulos et al., 2014; Broach and Dill, 2015; Montini et al., 2017).

D) Walkability in architecture, spatial and transport planning Studies in the last literature category are set apart from the others by a focus on improving transport and spatial practice and an emphasis on applicability. Cervero and Kockelman (1997) introduce the 3Ds (density, diversity and design) to describe the influence of the built environment on travel behaviour. Recently, Ewing and Cervero (2010) added two more Ds, destination accessibility and distance to transit. Although the 3 or 5 Ds can be measured reliably, they only describe walkability on a macroscopic, area-wide scale. In a reaction to the most recent meta-analysis on this topic by Stevens (2017), Handy (2017) stresses the absence of a theoretical framework and critically reflects on the use of sophisticated regression models without an underlying concept of pedestrian behaviour.

A walkability index encountered a number of times in the literature is the survey-based NEWS scale by Saelens et al. (2003). Cerin et al. (2007) confirms its validity in Hong Kong. Frank et al. (2010) developed a simpler walkability index based on residential density, retail floor area, intersection density and land use diversity. A third way of evaluating walkability is through the judgements of expert panels (Ewing et al., 2006).

The neighbourhood is the most common scale on which walk-friendliness is researched and assessed in the literature. In doing so, one risks neglecting the scale of perception of humans, which is much smaller. Some researchers who recognise this focus on individual street segments or cross-sections (Blecic et al., 2016). Ewing et al. (2006) define nine urban design qualities and let an expert panel rate them based on video sequences of streetscapes. Landis et al. (2001) suggests a pedestrian level-of-service defined by traffic volume, lateral separation and sidewalk attributes.

3.2 Meta-analyses in the literature

A comprehensive review of the existing literature was done by Saelens and Handy (2008). Based on 29 studies, this review lists the methodologies and results of individual sources and gives an overview of the relevance of walkability parameters. This is established by counting the sources that reported a positive or negative correlation between a parameter and the overall walkability. Density, land-use mix, network connectivity and personal safety are found to be most important. Their approach is closest to the one of this paper, displaying an extremely thorough familiarity with the existing literature on environmental determinants of walking, although it lacks a parameter-by-parameter overview or comparison.

Owen et al. (2004) conducted a review of 18 studies aimed at researching the relation between different environmental attributes and walking. For each attribute, the number of studies finding significant and insignificant association with walking is reported. The studies are also grouped by walking purpose. Aesthetics, the presence of walking infrastructure, accessibility of destinations and perceptions about traffic are reported as most influential. Proposing a novel walkability assessment method, Monteiro de Cambra (2012) reviews the literature and describes around 150 different indicators of walkability which then are used to construct a three level walkability score. The author comments that too often researchers in the field have created new measurement indicators without regard for their relevance or their perception by pedestrians. A final work of research worth mentioning is from Aghaabbasi et al. (2016) who evaluated sidewalk design factors. Both the investigated factors and existing walkability assessment tools are compared by thoroughly reviewing the literature. The summary of walkability assessment tools gives detailed lists of sidewalk indicators for all studies, as well as the research field (health or planning) from which the respective authors approached the issue.

Summing up, walkability scores or methodologies describing walkability parameters are well established in transport research. Their applications in practice are still quite rare, mostly confined to individual cities or regions. The most common ways of validating walkability indicators is through surveys or census data. Studies differ strongly both in their approach to the problem and their results, which leads to conceptual discrepancies that are interesting but difficult to interpret. Only few researchers choose attributes to focus on based on existing literature. Meta-analyses are scarce and quantitative results based on such approaches even more so.

4 Results

4.1 Literature collection

From the full set of 202 found sources, 24 studies are selected for meta-analysis. Only studies that explicitly describe their method and produce quantitative results are included, to allow for the comparison of effect sizes of walkability parameters. The 24 literature sources are described in Table 1. Most of the studies employ regression models, either to describe walkability directly, or in the form of route and mode choice models. Some only report bivariate correlations. In some cases a walkability rating method is taken from the literature or newly proposed. In terms of the used data, most studies feature some type of pedestrian survey or activity diary combined with environmental attributes, either self-reported by the study subjects or objectively derived from geo-referenced data. A smaller number of studies rely on available census data or expert panels. The criteria employed for deciding which studies to include in the meta-analysis are:

- Explicit definition of parameters examined for their influence walkability, including their units of measurement.
- Sufficient description of the used measurement or observation methods.
- A clear objective of correlating between the studies' parameters and pedestrian behaviour or perception of walk-friendliness.

Regarding the scale of analysis, as described above, five studies chose a microscopic approach, examining individual sidewalks or street segments. The majority of researchers focus on a mesoscopic level while six studies are done on a macroscopic (neighbourhood) level. The full list of literature sources and their respective categories are found as additional material in the online version of this paper.

4.2 Generalised parameters

By grouping all individually occurring parameters that describe the same quantity or influence in their respective source publications, 35 generalised walkability parameters were defined. They are listed in Table 2, together with their spatial scale and the number of literature sources from which they originate. For improved readability the parameters are grouped thematically to reflect the different aspects of walkability that are covered in the literature:

Table 2: Generalised walkability parameters covered in quantitative studies.

#	Walkability parameter	Generalised definition	Parameter count	Typical scale
	Walking infrastructure			
1	Presence of sidewalk	Presence of walkability infrastructure, possibly on either street side.	9	microscopic
2	Sidewalk continuity	Continuity of sidewalks (inversely: number of obstacles/interruptions).	8	microscopic
3	Sidewalk width	Width of sidewalk.	10	microscopic
4	Sidewalk surface	Smoothness, firmness or general quality of sidewalk surface.	6	microscopic
5	Sidewalk maintenance	Cleanliness and maintenance of the sidewalk.	5	microscopic
6	Crosswalks	Presence and density of crossing opportunities.	11	mesoscopic
7	Crossing signals	Presence and density of signalised crosswalks.	5	mesoscopic
8	Barriers	Longitudinal fences or hedges between sidewalk and road.	3	mesoscopic
9	Stairs/ramps	Presence of stairs or ramps.	3	microscopic
10	Slope	Slope value in walking direction or general hilliness.	6	mesoscopic
	Streetscape design			
11	Lateral separation	Lateral separation of sidewalk from the road (buffer).	5	mesoscopic
12	Visual complexity/landmarks	Visual complexity of the streetscape design, presence of landmarks.	4	mesoscopic
13	Design/proportions of streetscape	Proportions and design of street cross-section and buildings.	8	mesoscopic
14	Aesthetics	Measure of the visual appeal of streetscape and façade design.	6	mesoscopic
15	Street type	Type of street (pedestrian only or mixed).	4	mesoscopic
	Urban layout			
16	Land use diversity neighbourhood	Measure for land use diversity on the neighbourhood level.	11	macroscopic
17	Land use diversity street	Measure for land use diversity on the streetscape level.	3	mesoscopic
18	Retail/amenities	Accessibility to land uses and destinations.	4	macroscopic
19	Street connectivity	Density of the street network.	10	macroscopic
20	Residential density	Spatial density of residents.	6	macroscopic
	Comfort and safety			
21	Traffic safety	Safety for pedestrians from traffic accidents.	5	microscopic
22	Lighting	Presence of light during night time.	7	microscopic
23	Sidewalk furniture	Presence of street furniture such as benches or trash bins.	5	microscopic
24	Trees/green	Presence of trees or natural green along sidewalks.	6	microscopic
25	Traffic speed	Maximum speed of traffic.	3	mesoscopic
26	Social comfort	Presence of other pedestrians (e.g. buys streets).	4	mesoscopic
27	Crime	Risk of criminality for pedestrians.	8	macroscopic
28	Weather	Influence of bad weather on pedestrians.	4	macroscopic
29	Noise/pollution	Negative influence of noise or pollution.	4	macroscopic
	Transport interactions			
30	Traffic volume	Traffic volume on roads along sidewalks.	8	mesoscopic
31	Presence of cars	General presence of cars along sidewallks.	4	mesoscopic
32	Public transport	Presence (infrastructure/supply) of public transport	5	macroscopic
33	Parking	Presence of car parking spots along or on sidewalks.	3	microscopic
34	Presence of bicycles	Interactions between pedestrians and bicycles.	4	microscopic
	Various			
35	Distance	Influence of route length on pedestrians.	6	macroscopic
	Unsorted parameters	Unsorted parameters.	12	-

- **Walking infrastructure:** The type of parameters occurring most often. It includes all parameters related to the physical infrastructure on a mostly microscopic level such as the various properties of sidewalks. In general, these parameters can be measured objectively; an operational definition is usually possible.
- **Streetscape design:** Parameters describing the geometrical and visual appearance of streets. Their typical scale is mesoscopic. The aesthetic aspects of streetscapes are particularly difficult to measure and operationalise.
- **Urban layout:** Some of the most replicated and reproduced walkability correlates such as land use characteristics or measures of density and accessibility. Most popular in literature from the US and Australia, were the effects of urban sprawl are most noticeable.
- **Comfort and safety:** This type includes all aspects of the built environment related to comfort and safety. As a result, they tend to be more dependent on pedestrians' perception. Although the regions where most of the literature originates are objectively speaking very safe for pedestrians, perceived safety may vary strongly.
- **Transport interactions:** The interactions between pedestrians and other road users such as bicyclists are described by these parameters.

Twelve out of 215 parameters cannot be attributed to any of the generalised parameters. Six parameters describe walking distance, which is considered a special case and is thus not grouped with other parameters. The reasoning behind this is that walking distance is roughly proportional to trip duration, which is generally considered by far the most important influence on travel decisions. However, as the distance for a given trip is fixed, pedestrians will not easily recognise it as a bigger influence than for example the quality of one's surroundings or the volume of motorized traffic. Its quantitative impact is therefore difficult to gauge correctly. Furthermore, in a certain way distance acts as a multiplier of other walkability parameters: If a street segment has a certain undesired property, that property becomes a larger negative influence for longer segments. Walking distance can thus be regarded as a yardstick to calibrate walkability models, rather than simply one of its parameters.

4.3 Parameter rating

Ten of the 24 studies are suited for rating methods A and B. Of 215 original parameters, 49 can be used for Method A and 79 for Method B, with a significant overlap. This leads to rather small samples (in terms of the number of studies N contributing to the result) for some generalised parameters. Table 3 presents the results of the quantitative analysis and parameter ratings, including the number of original parameters included in the rating process. Only the generalised parameter "Noise/pollution" is not featured in any of the 10 studies that fulfil the requirements for either rating method, and can therefore not be ranked. The meta-analysis results are in the following section.

The criteria for inclusion in Method A are:

- Numerical values for standardized effect sizes of individual parameters on perceived walk-friendliness or walking activity.
- Reporting of the study sample size as a minimal descriptive statistic.

For a direct comparison between studies it is required that the reported standardized effect sizes are recorded as numerical values between 0 and 1, where 1 means that increasing the parameter in question by 1% results in an increase in walkability of 1%. In this field of research, the common way of reporting such elasticities is to calculate partial correlation coefficients from the study data. The criteria for inclusion in Method B are:

- Numerical values for the measure of influence of individual parameters on perceived walk-friendliness or walking activity. In most cases they are model coefficients.
- Comparability of the parameters within each respective study.
- Use of identical units for each measure/coefficient, or the possibility to transform them into the same units.
- Reporting of the study sample size as a minimal descriptive statistic.

As discussed above, Method B enables larger samples of studies for the calculation of quantitative effects of walkability parameters. As seen in Table 1, however, some studies are only suited for Method A. These studies focus explicitly on a subset of walkability parameters, usually those pertaining to land use. Because of this, the models in question usually feature only a handful of parameters. Both the specificity of the models and the low number of parameters may inflate the relative importance of each parameter, rendering misleading results. For this reason, the studies were left out of Method B.

The results of Methods A and B differ quite substantially. This is most notable for parameters that are featured in only one or two studies that can be used for Rating A, whereas more studies are available for Method B, providing a bigger sample to average over. This supports the assertion that Method B can be considered the more reliable one. A noticeable example is "Social comfort" which is of around average importance for walkability according to Method B, but ranks highest in Method A based on a single literature source reporting a remarkably large standardised effect size of 0.31.

Table 3: Results of the meta-analysis of walkability parameters. The selected literature is evaluated in terms of the number of parameters reported and found significant, their average effect size (β_M) and average relative importance (RI_M).

#	Walkability parameter	Parameter count (total)	Parameter count (significant)	Rating A sample	β_M (Method A)	Method B sample	RI_M (Method B)
	Walking infrastructure						
1	Presence of sidewalk	9	7	2	0.09	2	0.06
2	Sidewalk continuity	8	6	0	-	1	0.13
3	Sidewalk width	10	8	2	0.05	3	0.06
4	Sidewalk surface	6	3	0	-	2	0.12
5	Sidewalk maintenance	5	3	2	-0.02	2	0.03
6	Crosswalks	11	7	2	0.07	4	0.08
7	Crossing signals	5	2	1	0.00	2	0.00
8	Barriers	3	1	2	0.06	2	0.08
9	Stairs/ramps	3	1	1	-0.03	2	0.04
10	Slope	6	5	2	-0.07	4	0.14
	Streetscape design						
11	Lateral separation	5	5	1	0.14	1	0.08
12	Visual complexity/landmarks	4	3	0	-	3	0.08
13	Design/proportions of streetscape	8	3	3	0.09	5	0.03
14	Aesthetics	6	4	2	0.13	4	0.06
15	Street type	4	2	1	0.09	2	0.07
	Urban layout						
16	Land use diversity neighbourhood	11	8	5	0.07	3	0.07
17	Land use diversity street	3	3	0	-	1	0.08
18	Retail/amenities	4	3	2	0.11	2	0.04
19	Street connectivity	10	10	3	-0.09	3	0.17
20	Residential density	6	5	3	0.08	2	0.11
	Comfort and safety						
21	Traffic safety	5	4	1	0.06	2	0.09
22	Lighting	7	5	2	0.01	4	0.04
23	Sidewalk furniture	5	2	2	0.03	3	0.03
24	Trees/green	6	4	1	0.09	2	0.12
25	Traffic speed	3	2	1	0.12	1	0.06
26	Social comfort	4	3	1	0.31	3	0.09
27	Crime	8	7	1	-0.06	2	0.09
28	Weather	4	2	1	-0.07	1	0.04
29	Noise/pollution	4	4	0	-	0	-
	Transport interactions						
30	Traffic volume	8	6	0	-	1	0.04
31	Presence of cars	4	3	1	-0.03	3	0.13
32	Public transport	5	3	1	0.04	2	0.05
33	Parking	3	0	2	-0.07	3	0.08
34	Presence of bicycles	4	4	1	-0.17	1	0.09
	Various						
35	Distance	6	5	0	-	1	0.30
	Unsorted parameters	12					
	Totals	**215**	**143**	**49**		**79**	

5 Discussion and findings

Although 202 literature sources were found on the relationship between pedestrians and the built environment, only 24 were suited for meta-analysis. The main reasons for omission are a lack of clear parameter definitions, research methods not aimed at measuring quantitative relations and non-empirical or insufficiently described study approaches. Dividing the existing literature into categories offers a simple way to bring structure into the research field as well as this meta-analysis. The data collection can be expanded as more studies appear. The generalised definition of walkability parameters (Table 2) is based on all parameters found in the literature but also on the authors' judgement and should be treated as an initial suggestion. Studies focused on few parameters or specific aspects of walkability, (e.g. Kang and Fricker, 2016), tend to offer more precise parameter definitions. Studies with many parameters often employ regression models and present less information about the exact nature of parameters.

Many of the analysed studies introduce their parameters without detailed justification. Others, like Moura et al. (2017), choose parameters based on the literature or employ existing walkability measuring tools (Kim et al., 2016). Parameters pertaining to the urban layout like population density and land use diversity were included in the earliest walkability studies (mostly literature types A and D). This choice might be attributed to the goals and interests of the researchers in question, rather than an attempt to prioritise the most impactful parameters. Whichever the case, the scientific process of determining the relevant parameters is often omitted. For the most part, the relevance of the chosen built environment variables is obvious: Sidewalks are essential for pedestrians and it is not surprising that most studies include their properties.

The results offer four different ways of evaluating and comparing walkability parameters: The bare parameter count, representing the number of times a parameter was encountered in the literature, the significant count, representing the number of times the parameter was found to be statistically significant, its quantitative effect size (Method A) and its relative importance (Method B). The first measure can be viewed as a basic assessment of the relevance of a certain environmental attribute to the walk-friendliness of an area. It is unlikely, though not impossible, that fundamentally new properties of the built environment will be found to have a profound impact on walkability. A counterargument to this could be the presence of bicycles, which for a long time were seen as "siblings" to pedestrians, both representing environmentally friendly modes for short trips. Only recently have scholars focused on possible negative interactions between the two and despite the low number of times the presence of bicycles was encountered in the literature (see Tables 1 and 2), it is among the bigger influences on walk-friendliness according to both ratings A and B.

The second way of assessment, the number of times a parameter was reported as significant, can

Table 4: Weighted average relative importance rating of environmental parameters of walkability (Rating Method B).

#	Walkability parameter	Parameter count	RI_M (Rating B)
35	Distance	1	0.30
19	Street connectivity	3	0.17
10	Slope	4	0.14
31	Presence of cars	3	0.13
2	Sidewalk continuity	1	0.13
4	Sidewalk surface	2	0.12
24	Trees/green	2	0.12
20	Residential density	2	0.11
34	Presence of bicycles	1	0.09
26	Social comfort	3	0.09
21	Traffic safety	2	0.09
27	Crime	2	0.09
6	Crosswalks	4	0.08
17	Land use diversity street	1	0.08
8	Barriers	2	0.08
12	Visual complexity/landmarks	3	0.08
33	Parking	3	0.08
11	Lateral separation	1	0.08
16	Land use diversity neighbourhood	3	0.07
15	Street type	2	0.07
25	Traffic speed	1	0.06
1	Presence of sidewalk	2	0.06
3	Sidewalk width	3	0.06
14	Aesthetics	4	0.06
32	Public transport	2	0.05
18	Retail/amenities	2	0.04
9	Stairs/ramps	2	0.04
30	Traffic volume	1	0.04
22	Lighting	4	0.04
28	Weather	1	0.04
5	Sidewalk maintenance	2	0.03
23	Sidewalk furniture	3	0.03
13	Design/proportions of streetscape	5	0.03
7	Crossing signals	2	0.00
29	Noise/pollution	0	-

be considered a check on the first: If a parameter is researched very frequently, but oftentimes is found to be statistically insignificant, it might merely have a reputation of being important to walkability while not actually being so. The opposite might be the case for parameters mentioned infrequently, but reliably testing as significant, like the aforementioned presence of bicycles.

The biggest value of the meta-analysis lies in the quantitative estimation of a certain parameter's effect size according to rating Methods A and B. However, for most generalised parameters these are based on very small samples. The results should therefore be interpreted with caution. Nevertheless, when ranked from highest to lowest in terms of Method B (as seen in Table 4) the relative importance of the 35 parameters seems plausible and in accordance with the literature. As discussed above, while both methods have their advantages and disadvantages, RI_M is put forward as the more reliable measure, as it is based on a larger sample of coefficient values. Furthermore, the exact values for RI_M are less meaningful than their relative positions within the ranking list.

For most parameters with high RI_M values, the importance for walk-friendliness is obvious. Walking uphill or in the close vicinity of through-traffic is clearly unattractive for most people. Likewise, the continuity and surface of a sidewalk have an obvious impact on one's comfort. Of the "3 D's" featured throughout the walkability literature, only "Design", in the form of the generalised parameter "Street connectivity" is found near the top of the list. This relates to the previous discussion on the pivotal role of distance: A well-connected network of walking infrastructures makes for more direct walks with fewer detours. It should be noted, however, that the study with the largest sample size reports a negative influence of street connectivity on walkability. Its authors theorise that this is due to the frequent need to cross traffic.

Figure 1: Visual representation of the relative importance of walkability parameters.

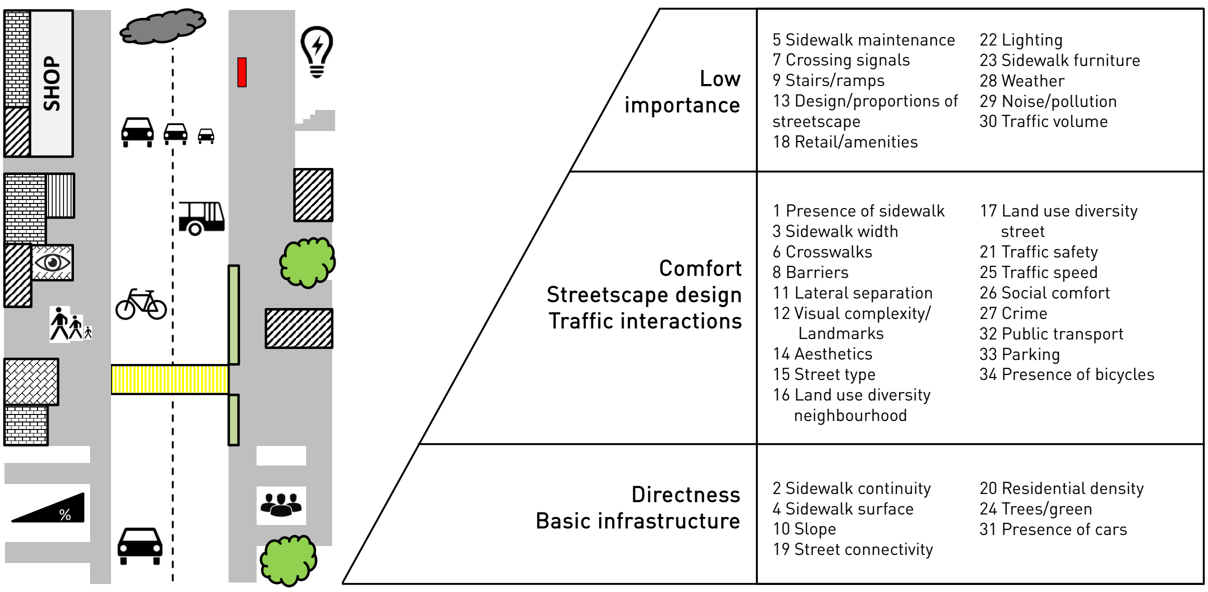

Figure 1 is an graphical representation of the parameter ranking according to their RI_M values. This enables a quick overview of the meta-analysis results on a three-level scale where the basic level (displayed at the bottom, $RI_M>0.1$) contains the most important parameters that should be part of planning any built environment. The attributes on middle level ($RI_M<0.05$) are somewhat less relevant but still required for any pedestrian-friendly place, while the third level consists of environmental attributes with a low, albeit generally measurable, effect on pedestrians. The schematic streetscape on the left symbolises the parameters on their respective levels.

6 Conclusion

The research presented in this paper aims to identify which aspects of the built environment have the highest impact on walkability. 215 walkability parameters from 24 literature sources are systematically categorised, leading to generalised definitions of 35 environmental parameters that influence the perceived walk-friendliness of a street or an area. Furthermore, the effect sizes and relative importances of said parameters are estimated using two methods of meta-analysis. Travel distance, street connectivity and the slope of terrain are found as the three most important determinants of walk-friendliness.

Because of the multi-levelled structure of the meta-analysis and the systematic approach to filtering the comparable parameter coefficients and effect sizes from the literature, the explanatory power of the findings is deemed substantial. With regard to the initial research question of identifying environmental influences on walkability, the results enable a ranking of walkability influences. Furthermore, they offer interesting insights in the role of different aspects of the built environment and practically applicable values for planners and engineers to use. For future research, the highest potential may lie in applying more standardised methods to this field of research to ensure that different studies measure the same effects and report the same measures. The authors recommend calculating partial correlation coefficients as the main findings of future research.

Examining specific parameters and their influence on pedestrian would highly improve the understanding of their influence on pedestrians. The studies by Kang et al. (2013) and Kang and Fricker (2016) for example focus solely on the pedestrian-bicycle interaction and thereby provide valuable practical information regarding this one parameter. The results of such studies are vital for a more in-depth understanding of each individual parameter. The pyramid-like representation of the relative importance of walkability parameters presented in Fig. 1 provides a framework for choosing parameters to focus on and operationalising the knowledge thus gained.

For future research on walkability and pedestrians' perception of and interactions with the built environment, the authors suggest to focus more on the pivotal role of walking distance. On the one hand, the built environment largely determines walking distances via the distribution of residences, activities and destinations. On the other hand, the quality experienced while covering those distances is determined by other aspects of the built environment. The authors argue that a full grasp of these interactions is crucial for the creation of better pedestrian environments and for strengthening the role of walking in the transport system.

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